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Comparison of OFDMA and SC-FDMA Channel Access Techniques in a Passive Optical Network Environment

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Abstract: For the first time, OFDMA and SC-FDMA are compared experimentally as candidate uplink access techniques for next-generation PONs. Important issues like peak-to-average power ratio, optical beat interference, and symbol delay are studied and experimentally measured.

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1. Introduction

Orthogonal frequency division multiple access (OFDMA) and single-carrier frequency division multiple access (SC-FDMA), two enabling multi-user access methods for fourth generation (4G) wireless communication, have recently been studied extensively as potential candidate techniques for next-generation passive optical network (NG-PON) [1, 2]. Both of which exploit multi-level, orthogonal frequency division multiplex (OFDM) signaling making possible the NG-PON with higher spectral efficiency and longer reach. In addition, the flexible resource allocation of OFDMA/SC-FDMA in frequency and time enables heterogeneous services delivery over a unified PON platform while allowing leveraging legacy optical distributed network (ODN) to save on capital expenditure. Although both OFDMA and SC-FDMA have been demonstrated as either PON downlink or uplink, the distinction between their impacts to the NG-PON is still a blur. Therefore, as part of the research effort to investigate on this issue, in this paper, we conducted the first experimental study on the comparison of OFDMA and SC-FDMA as PON uplinks. Special attention was paid to the peak-to-average power ratio (PAPR) of both uplink signals and their performance assessment over an identical analog multipoint-to-point (MP2P) optical test link. In addition, other technical issues like optical beat interference (OBI) and relative symbol delay between MP2P optical upstream tributaries were discussed and experimentally measured, both of which are key system parameters when designing a robust uplink path for the NG-PON based on either OFDMA or SC-FDMA.

2. OFDMA vs. SC-FDMA: PAPR Analysis

One of the most rigorous ways to analyze PAPR is to characterize the peak power statistics of a modulated signal through complementary cumulative distribution function (CCDF) giving the probabilities of signal's PAPR exceeding specific PAPR values ($PAPR_0$). Fig. 1 illustrates the simulated CCDFs for OFDMA and SC-FDMA signals at different modulation levels, respectively. Both OFDMA and SC-FDMA cases have similar fundamental parameters: 128 subcarriers per OFDM symbol, cyclic prefix (CP) length of 10, five OFDM symbols per slot with middle one serving as a reference signal, 2.5×10^6 slots were calculated with a single slot duration of 4.38 μs, over sampling rate of 12, and two optical network units (ONU) were considered individually containing 54 subcarriers at a localized mapping mode. In addition, square root raised cosine pulse shaping with a roll-off factor of 0.2 was applied for both cases. As shown in Fig. 1, at all modulation levels SC-FDMA has significant lower $PAPR_0$ than that

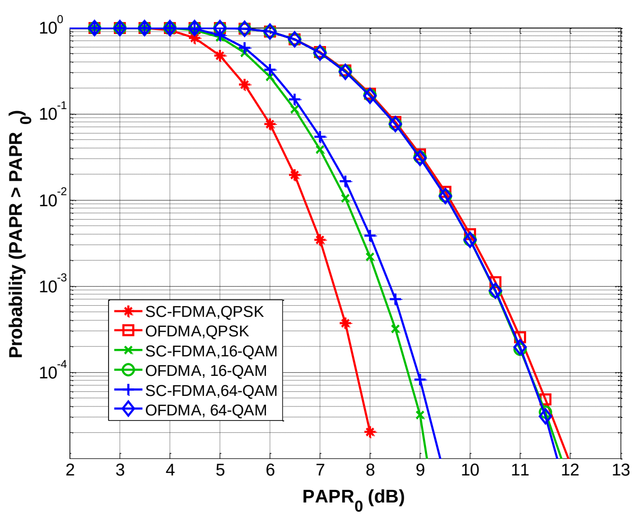

Fig. 1 Simulated CCDF of PAPR for OFDMA and SC-FDMA signals at modulation levels of QPSK, 16-QAM and 64-QAM, respectively.

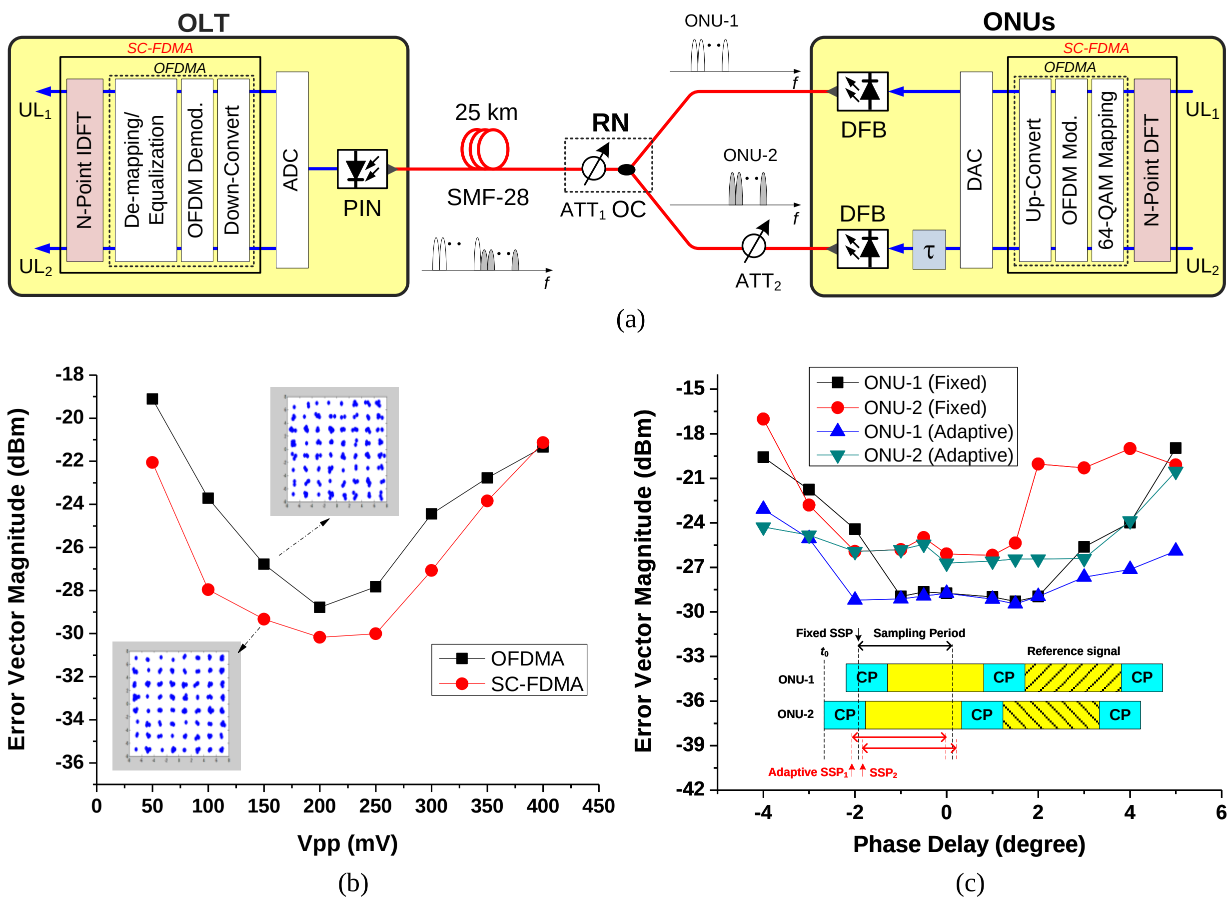

Fig. 2 (a) proof-of-concept experimental setup for a NG-PON employing OFDMA and SC-FDMA as uplink access techniques, respectively, measured EVMs as a function of (b) V_{pp} of OFDMA and SC-FDMA uplink signals and of (c) relative phase delay between SC-FDMA symbols from different ONU using fixed and adaptive SSPs for signal decoding, respectively.

of OFDMA. For example, with the same probability of 10^{-1}, the $PAPR_0$ of SC-FDMA is about 1.5 dB lower than that of OFDMA at 64-QAM. Such low PAPR nature of a SC-FDMA signal is expected to play a key role as an analog PON uplink where the end-to-end linearity is of utmost concern.

3. Experimental Setup and Results

Fig. 2(a) shows the experimental setup for assessing the performance of OFDMA and SC-FDMA signals in a PON uplink environment, respectively. This optical MP2P uplink testbed included two optical network units (ONUs), individually equipped with a 2.5-GHz analog un-cooled DFB laser transmitter with 10-dBm output power. Uplink paths were then combined in a remote node (RN) consisting of a 1×2 optical combiner (OC) and a tunable attenuator (ATT_1) for emulating an actual insertion loss at high splitting ratio. After transmitted over a 25-km standard single-mode fiber (SMF-28), the aggregated uplink signals were detected by a 2.5-GHz analog PIN photoreceiver at the optical line terminal (OLT). Another tunable attenuator (ATT_2) and a phase shifter (τ) were arranged along the uplink path from ONU-2 to RN to investigate on the power-dependent OBI as well as the impacts of relatively symbol delay, respectively. This test link was designed with minimal requirements of a spurious-free dynamic range (SFDR) of 100 $dB/Hz^{2/3}$ at 1Hz bandwidth, a RF gain of around 12 dB, a noise figure of 18 dB, and a 1-dB compression point at -14 dBm. In addition, as shown in Fig. 2(a), there are many similarities between OFDMA and SC-FDMA signal generation and reception, and the significant difference is that SC-FDMA requires additional functional blocks of N-point discrete Fourier transform (DFT)/inverse discrete Fourier transform (IDFT) before/after OFDM modulation/demodulation with M-point (M>N) IDFT/DFT at the ONU/OLT, respectively. The detailed physical-layer functions for both OFDMA and SC-FDMA can be found in [3]. The OFDMA and SC-FDMA signals for the experiment were generated via off-line DSP programs with the same parameters described in Section 2, and modulation level of 64-QAM was chosen so that the achievable aggregated uplink data rate is about 1 Gb/s with a

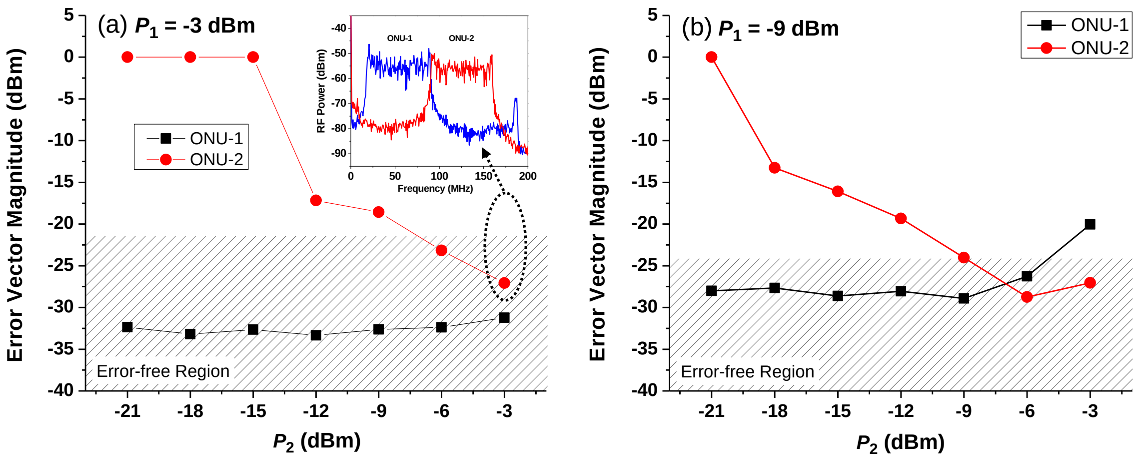

Fig. 3 EVMs of SC-FDMA uplinks from ONU-1 and ONU-2 as a function of P_2 when P_1 was fixed at (a) -3 and (b) -9 dBm, respectively

total occupied RF bandwidth of 166.6 MHz, which is much less than the modulation bandwidth of DFB transmitters.

Fig. 2(b) shows the received error vector magnitude (EVM) versus the peak-to-peak RF driving voltage (V_{pp}) of OFDMA and SC-FDMA, respectively. With V_{pp} below 400 mV SC-FDMA signal has lower EVM by as much as 4dB when both ONUs are active. The insets depict the received 64-QAM constellations. Other than PAPR, there still have two technical issues applied to both SC-FDMA and OFDMA as PON uplinks, and should not be overlooked: symbol delay and optical beat interference (OBI). The former is due to the fact that the transmission distance between RN and ONUs may differ up to several kilometers, which may be overcome by increasing the CP length at the cost of efficiency reduction, while the latter occurs when two or more optical lightwaves at nearby frequencies transmit over the same optical channel and are simultaneously detected by using a single square-law photodetector, which may introduces cross-mixing terms as beat noise deteriorating the original signals. Therefore, in Fig. 2(c) we measured the EVM as a function of phase delay between SC-FDMA uplink symbols from two ONUs, in which the signal decoding was done by employing fixed (traditional) and adaptive (proposed) sampling starting point (SSP), respectively. As illustrated in the inset, when the ONU-1 frame was delayed, most likely a conventional fixed SSP may not be the optimized point for both frames. However, by using maximum likelihood (ML) method based upon the reference signals, the proposed scheme is able to find the optimized SSP adaptively for each frame, and results in a better EVM performance over a certain phase delay range between -4 to 5 degrees as displayed in Fig. 2(c). Note that, both schemes were operated in the same condition that the maximum allowable delay time should not exceed a CP length under the scheduling control at OLT. In addition, we investigated on the OBI through the measurement of EVMs for SC-FDMA uplinks at various received optical power of ONU-2 (P_2) when that of ONU-1 (P_1) was kept constant. In Fig. 3(a), with P_1 fixed at the highest power of -3 dBm, the EVM of ONU-2 increased dramatically as P_2 reduced, and P_2 should not be lower than -7 dBm to claim an error-free transmission for both uplinks. The inset shows the measured RF spectra of ONU-1 and ONU-2 uplinks. Similarly, in Fig. 3(b) when P_1 was fixed at a lower power of -9 dBm, P_2 should be maintained between -9 dBm and -5 dBm. As a result, it was evident that OBI has significant impacts on those input optical signals with lower power level, and a limited dynamic range of received optical power of 4 dBm was observed.

4. Conclusions

We conducted the first experimental comparison of both OFDMA and SC-FDMA uplinks at 64-QAM in a PON environment. SC-FDMA uplink exhibited better EVM performance than OFDMA one by 4 dB over 25-km SMF-28 due to its intrinsic low PAPR. A limited 4-dBm dynamic range of received optical power was observed resulting from the optical beat interference between SC-FDMA uplinks. In addition, a higher system tolerance to the symbol delay was experimentally demonstrated using the proposed adaptive sampling starting point.

5. References

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